

# Properties of High Redshift Cluster Ellipticals

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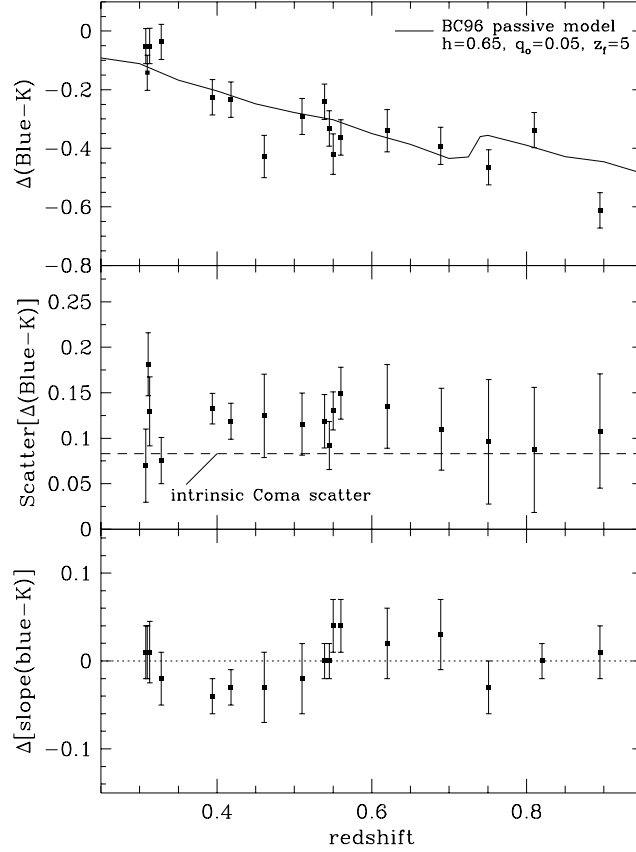
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**Abstract.** Cluster ellipticals are often thought to be among the oldest galaxies in the universe, with the bulk of their stellar mass formed at early cosmic epochs. I review recent observations of color evolution in early-type cluster galaxies at high redshift, which show remarkably little change in the color-magnitude relation out to  $z \approx 1$ . Spectra of elliptical galaxies from  $1.15 < z < 1.41$  demonstrate the presence of a dominant old stellar population even at these large lookback times, although there is some evidence for a tail of later star formation. The Kormendy relation, a photometric/morphological scaling law for elliptical galaxies, is used to extend fundamental plane investigations to  $z = 1.2$  and to test for luminosity evolution. While the evidence, overall, is consistent with simple and mild passive evolution, I review some caveats and briefly consider the data in the light of hierarchical galaxy formation models.

## 1 Color evolution at $z < 1$

Rich clusters remain the most “efficient” place to find and study high redshift elliptical galaxies – they are abundant in such environments, even at  $z > 0.5$ , and the richness of the cluster ensures that a statistical analysis of their colors or image properties (in the absence of extensive spectroscopy) should not be too strongly biased by field galaxy “interlopers.” Until recently, studies of distant cluster ellipticals were predicated on selecting them by color or spectral properties, e.g. by analyzing the colors of the “red envelope” of the galaxy distribution and assuming that any changes reflect the evolution of the early-type galaxy population (e.g. Aragón-Salamanca *et al.* 1993). While sensible, this approach requires a reliable statistical means of identifying and measuring properties of galaxies in a one-sided distribution – e.g. the “reddest objects” in a given cluster – and risks missing important results if, for example, some *bona fide* ellipticals are substantially bluer than their reddest counterparts.

Now, however, a very extensive collection of WFPC2 images of high redshift clusters has amassed in the HST archive, enabling the armchair astronomer to ponder hundreds of high redshift ellipticals at will, selecting them on the basis of image morphology rather than color. The “MORPHS” collaboration (Dressler, Oemler, Ellis & many co-workers) have been responsible for collecting much of this data, and have recently analyzed the properties of early-type galaxies in three clusters at  $z \approx 0.55$  (Ellis *et al.* 1997). In particular, they have examined the scatter in the elliptical galaxy color-magnitude (c-m) relation. Bower *et al.* (1992) used the very small scatter in the c-m relation for Coma and Virgo ellipticals to argue that these galaxies have had highly synchronous evolutionary histories: they either formed at very large redshifts, or with nearly identical



**Fig. 1.** Color evolution of early-type cluster galaxies out to  $z = 0.9$ , from Stanford, Eisenhardt & Dickinson 1997. The data consist of optical and infrared photometry of early-type galaxies selected from WFPC2 images of high redshift clusters. The “blue” band is chosen for each cluster to remain approximately fixed at the rest-frame  $U$ -band, while the  $K$  band remains fixed in the observer’s frame. *Top*: differences in mean  $blue - K$  colors relative to the same rest-frame colors in the Coma cluster. “No evolution” would therefore be a horizontal line at  $\Delta(blue - K) = 0$ . *Middle*: intrinsic scatter in early-type galaxy colors, after removing the mean slope of the color-magnitude relation and the component of scatter due to photometric errors. *Bottom*: differences in the slope of the  $(blue - K)$  vs.  $K$  color-magnitude relation, relative to the slope measured for Coma.

subsequent star formation histories, or both. Ellis *et al.* find the same to be true in the three clusters they examined at  $z \approx 0.55$ , reinforcing the evidence for synchronized evolution.

Adam Stanford, Peter Eisenhardt and I have collected 5-band optical/IR imaging of a large sample of distant galaxy clusters (46 to date from  $0 < z < 0.9$ ), taking care to match both the field of view (in Mpc) and the rest-frame limiting luminosity of the data for each cluster in order to provide a uniform data set. The optical/CCD observations were taken through two filters which are matched to the cluster redshift in order to approximately sample the rest-frame  $U$  and  $V$  regions of the spectrum, while the near-IR  $JHK$  data provide a long wavelength baseline for measuring colors and ensure that galaxies may be selected uniformly by the luminosities of their old stellar populations, even at  $z = 1$ .

Returning from the telescopes to our armchairs, we have used archival WFPC2 data to identify early-type galaxies, independently from their colors, in 19 clusters, and to study their photometric evolution (Stanford, Eisenhardt & Dickinson 1997). We have used new wide-field imaging of Coma cluster in the  $UBVRIZJHK$  bands (Eisenhardt *et al.* 1997) to provide a present-day reference sample, ensuring that we can compare the properties of the distant cluster galaxies to data on nearby ellipticals at the same rest-frame wavelengths with only minimal differential  $k$ -corrections. Figure 1 summarizes this work, showing the evolution of the galaxy colors, and of the scatter and slope of the color-magnitude relation, out to  $z = 0.9$ . The key results are:

- The mean color of early-type cluster galaxies becomes gradually and monotonically bluer toward higher redshifts, in a fashion broadly consistent with simple passive evolution of the stellar populations.
- The scatter of galaxy colors around the mean color-magnitude relation remains small and nearly constant with redshift out to  $z = 0.9$ .
- The slope of the color-magnitude relation remains unchanged from  $z = 0.9$  to the present. This strongly supports the hypothesis that the  $c$ - $m$  slope is primary due to differences in the mean metallicity of elliptical galaxies as a function of luminosity/mass, and is not a consequence of differing ages (Kodama & Arimoto 1997; see also contribution of Arimoto to this volume).

The small and constant scatter in the galaxy colors is remarkable and somewhat difficult to explain. In particular, if ellipticals in all clusters were a completely coeval population, and if the small but non-zero scatter observed in their colors at  $z = 0$  (Bower *et al.* 1992) were due to age variations, then one would naively expect the scatter to increase at higher redshift. Although the mean scatter in the distant clusters is slightly higher than that measured for Coma, no other strong trend with redshift is observed. It may be that the intrinsic scatter at  $z = 0$  is due, in part, to metallicity variations at a fixed mass rather than to age differences. This would set a “floor” value to the scatter, suppressing the expected decrease with decreasing redshift. In this case, however, intrinsic age variations must be even smaller than the values inferred directly from the color scatter. Alternatively, small episodes of later star formation due to mergers, etc. may “re-inflate” the scatter in a more-or-less continuous fashion, but again the

amount of late star formation is strongly constrained by the small amplitude of the measured scatter. The 0.11 magnitude scatter observed for the most distant cluster in our sample, GH0 1603+4313 at  $z = 0.895$ , limits small (e.g.  $\leq 10\%$  by mass) star formation episodes to have occurred no less than 2 Gyr prior to the epoch of observation.

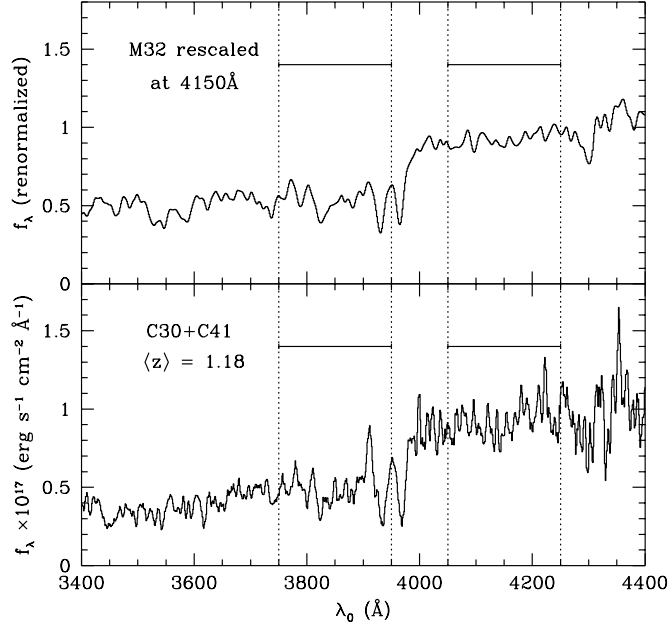
## 2 Spectroscopic characteristics of ellipticals at $z > 1$

The lack of dramatic change in the color properties of early-type cluster galaxies out to  $z = 0.9$  suggests that, by that redshift, we have not closely approached the era in which those galaxies formed the bulk of their stars. This therefore encourages us to extend the search for distant clusters and cluster ellipticals to higher redshifts. Peter Eisenhardt and I have been studying the environments of distant radio galaxies in order to search for distant galaxy clusters (cf. Dickinson 1995, 1997a, 1997b). Spinrad, Dey, Stern, LeFèvre and I have obtained extensive spectroscopy of one such cluster, that around 3C324 at  $z = 1.206$ . Using deep WFPC2 imaging and infrared photometry, we have identified elliptical galaxies in this cluster, as well as several in a “foreground” structure at  $z = 1.15$  and one background elliptical at  $z = 1.41$ .

Figures 2 and 3 present coadded Keck/LRIS spectra of three of these galaxies, showing the rest-frame optical and near-UV regions and identifying some of the prominent spectral breaks which are useful as diagnostics of the stellar populations. The  $z \approx 1.2$  galaxies exhibit a strong 4000Å break and CaII H+K lines, features prominent in the spectra of old stellar populations today. The near-UV spectra are strikingly similar to that of M32, although they are somewhat bluer (more flux at  $\lambda_0 < 2600\text{Å}$  relative to that at  $\lambda_0 \approx 3100\text{Å}$ ) and the discontinuities at 2640Å and 2900Å have somewhat smaller amplitudes.

Dunlop *et al.* (1996) have recently presented spectra of the faint, red radio galaxy 53W091 at even larger redshift,  $z = 1.552$ , which exhibits very similar UV spectral breaks at 2640Å and 2900Å. Spinrad *et al.* (1997) have analyzed the 53W091 data, making extensive comparisons to the ultraviolet properties of stars in the IUE spectral atlas, to nearby elliptical galaxies, and to population synthesis models – the reader is referred to that paper for a more thorough discussion, as well as to Charlot, Worthey & Bressan (1996) for an excellent review of potential pitfalls in the use of the evolutionary models.

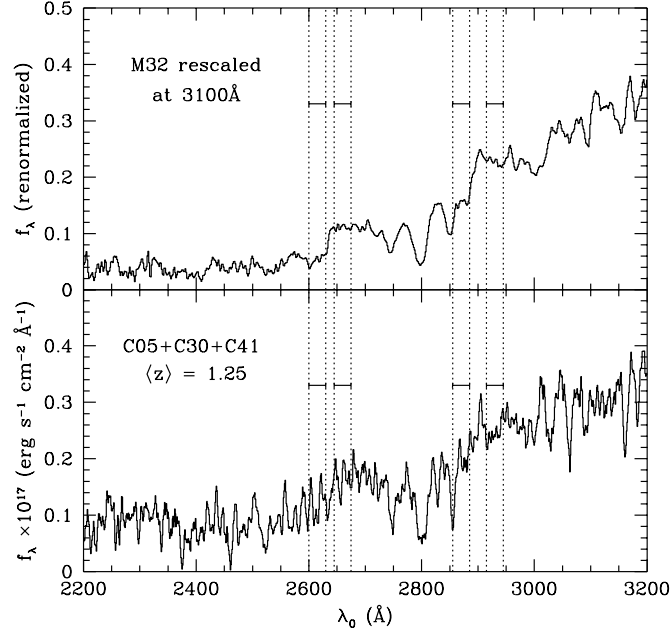
Here, we restrict our comparison to a single set of evolutionary models, those of Bruzual & Charlot (1996), which utilize model stellar atmospheres and evolutionary tracks to investigate the spectrophotometric evolution of stellar populations with various metallicities. Figure 4 shows the dependence of four indices (the three spectral breaks plus the  $R - K$  color) on age and metallicity for simple Salpeter IMF models ( $10^7$  yr burst followed by purely passive evolution). The horizontal dashed lines mark the index values for the 3C324 galaxies. All four indices exhibit the familiar age-metallicity degeneracy (e.g. Worthey 1994) – redder colors or larger break value may be matched either by older or more metal rich stellar populations. Spinrad *et al.* review evidence that an approxi-



**Fig. 2.** Coadded spectra in the rest-frame  $4000\text{\AA}$  region of two elliptical galaxies at  $z = 1.15$  and  $1.21$  in the field of 3C324 (bottom) compared to that of M32 (top). A very prominent  $4000\text{\AA}$  break and CaII H+K lines are visible; the spectral regions used to define the D4000 break amplitude are marked.

mately solar metallicity is an appropriate average value for giant ellipticals; we leave this problem unresolved here, but note that by studying the spectral properties of galaxies over a large range of cosmic time (rather than at a single, large redshift) we may eventually hope to break this degeneracy, as different rates of evolution would be expected for different metallicities.

Inspecting the four panels, one finds that the “age” derived from the various indices becomes “younger” the farther into the UV we look. Moving from red to blue indices (D4000,  $R - K$ , B2900 and B2640), and taking the solar metallicity model for reference, the ages derived for the single-burst model are approximately 4.5, 3.5, 1.7 and 0.5 Gyr, respectively. This suggests that the single, short-burst star formation history is not strictly correct, and that younger starlight plus an increasing role as one moves farther into the rest-frame UV. Models with more protracted star formation histories (e.g. exponentially decaying) or with later bursts can be constructed which reasonably match the data. However, the large  $4000\text{\AA}$  break amplitude and  $R - K$  color strongly indicate that the bulk of the stars in these galaxies must have formed *at least* 2 Gyr prior to  $z = 1.2$ , even for populations with super-solar metallicities. For an open, 13 Gyr-old universe ( $H_0 = 75$ ,  $q_0 = 0$ ) this places the formation redshift for



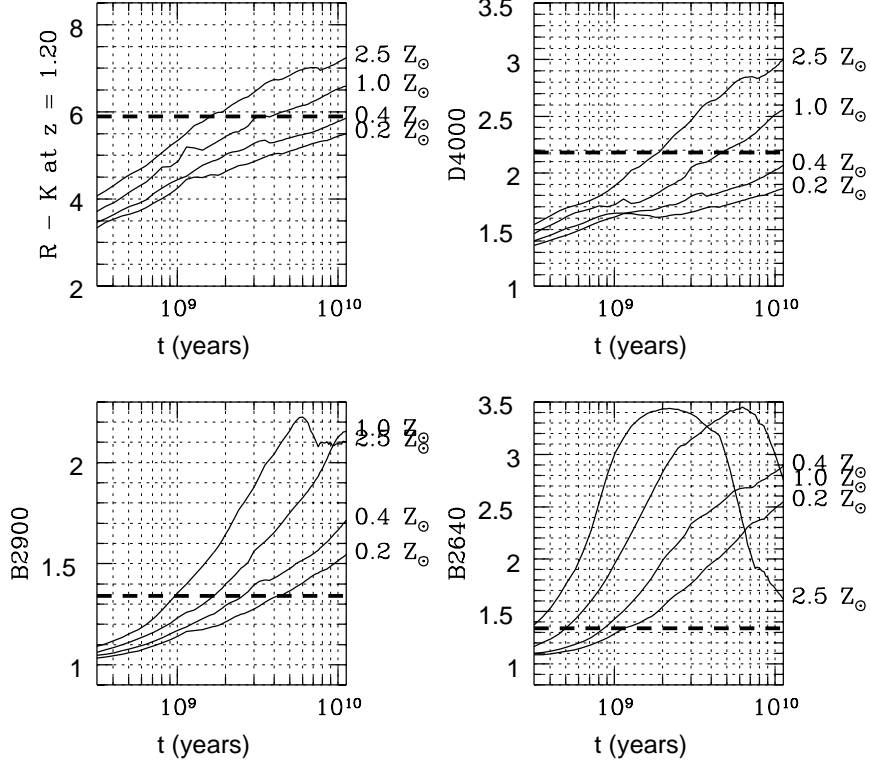
**Fig. 3.** Coadded near-UV rest-frame spectra of three elliptical galaxies at  $z = 1.15$  to  $1.41$  in the field of 3C324 (bottom) compared to an IUE spectrum of M32 (top). The strong MgII 2800Å absorption feature is clearly seen in the high redshift objects, flanked by MgI 2852Å and the absorption blend (primarily Fe+Cr) at 2746Å. The dotted lines mark the 2640Å and 2900Å break features defined by Spinrad *et al.* 1997.

the bulk of the stellar mass very conservatively at  $z > 2.3$ , and most probably higher. For a closed universe, formation can be pushed back to almost arbitrarily large redshifts.

### 3 Scaling relations to $z = 1.2$

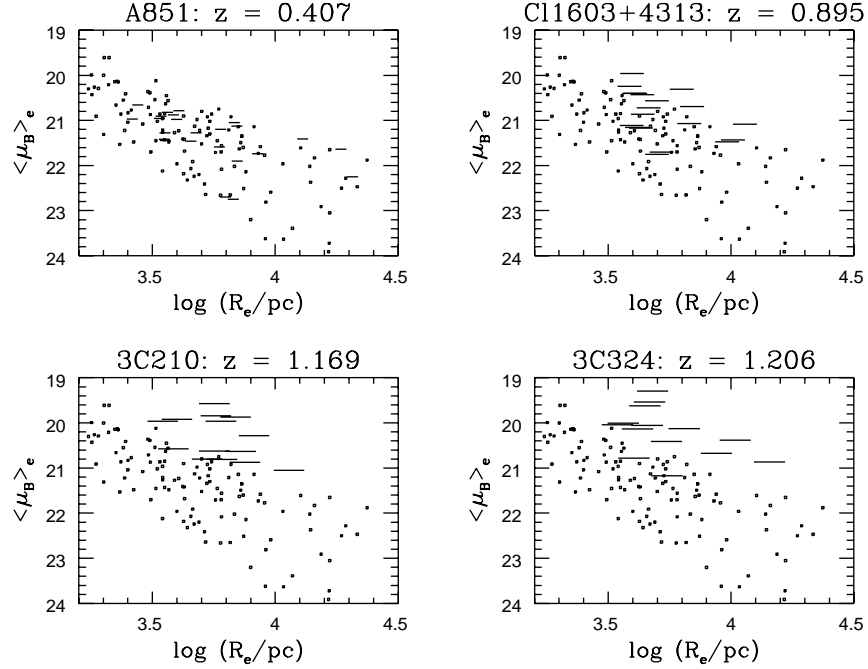
Some of the most exciting data shown at this meeting have been the fundamental plane and Mg- $\sigma$  observations at  $0.1 < z < 0.6$ , presented in the contributions of Bender, Franx, Jørgensen, Pahre, van Dokkum, and Ziegler to these proceedings (cf. also van Dokkum & Franx 1996 and Kelson *et al.* 1997). The conclusions of these various studies have been strikingly uniform: that the mass-to-light ratios of early-type galaxies in distant clusters have evolved very mildly, in a manner approximately consistent with expectations from simple, passive evolution of their stellar populations.

At present it is still difficult to extend this work to much larger redshifts, even with 10m-class telescopes, because the galaxies become extremely faint and the spectral features of interest for measuring velocity dispersions or Mg



**Fig. 4.** Simple models of passive evolution of a stellar population formed in a  $10^7$  year burst with a Salpeter IMF, computed using the code of Bruzual & Charlot (1996) for various metallicities. The panels show the expected amplitudes of three spectral “breaks” and the  $R-K$  broad band color. The  $R$ -band measures rest-frame light at  $\approx 3150\text{\AA}$  for  $z = 1.2$ , and thus is primarily sensitive to evolution at UV wavelengths intermediate between those measured by the  $4000\text{\AA}$  and  $2900\text{\AA}$  breaks. The horizontal dashed lines indicate the values measured for the  $z > 1$  ellipticals discussed in the text.

indices shift into the near infrared where they are horrendously impacted by OH night sky emission. In the absence of high-S/N, high dispersion spectroscopy at  $z > 0.8$ , we may at least take advantage of purely photometric/morphological projections of the fundamental plane which allow us to push studies of galaxy scaling relations to higher redshifts. For example, the Kormendy relation is the projection of the fundamental plane onto the size vs. surface brightness axes, and is thus highly suitable for study using HST WFPC2 images alone. Dickinson (1995), Pahre *et al.* (1996), Barrientos *et al.* (1996), and Schade *et al.* (1996

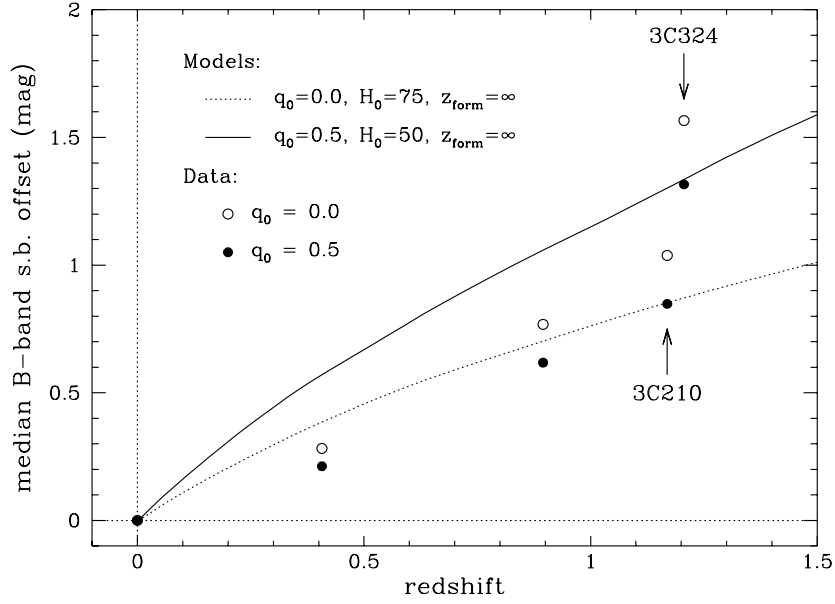


**Fig. 5.** The Kormendy relation for four high redshift galaxy clusters observed with HST. The small points are a sample of local cluster galaxies observed by Jørgensen *et al.* (1995). The horizontal lines represent individual high redshift ellipticals, and connect the  $R_e$  values for  $q_0 = 0$  and  $q_0 = 0.5$  ( $H_0 = 50$  assumed throughout).

and this volume) have all employed variants on this technique. The method has the advantage of requiring only high-resolution imaging data which is readily obtained for a large number of cluster galaxies per WFPC2 field, but it lacks the precision of the direct fundamental plane measurements (due to the larger scatter in the Kormendy relation); moreover without the kinematic data offered by spectroscopy one cannot directly connect the observables to evolution in the mass-to-light ratio of distant galaxies.

Figure 5 presents an update on the data shown in Dickinson (1995), demonstrating the Kormendy relation in the rest-frame  $B$ -band for four high redshift clusters, including two at  $z \approx 1.2$ . As one moves to higher redshifts, the cluster galaxies lie increasingly “above” the locus of low-redshift ellipticals, indicating either higher rest-frame surface brightnesses, larger effective radii, or some combination thereof. It is simplest, but not definitive, to interpret this as a manifestation of passive luminosity evolution. Figure 6 plots the median offsets of the Kormendy relation for each cluster from the local values, and compares them





**Fig. 6.** Median rest-frame  $B$ -band surface brightness offsets of distant cluster ellipticals relative to the local Kormendy relation.

with expectations from passively evolving Bruzual–Charlot (1996) models for two different cosmologies, each assuming present-day ages for galaxies (and the universe as a whole) of 13 Gyr. The two  $z \approx 1.2$  clusters seem to differ significantly from one another, but it is important to note that the 3C324 data was obtained with the WFPC2 F702W filter, which samples the cluster galaxy light at a rest frame of  $\lambda_0 \approx 3200\text{\AA}$ , requiring a large (and uncertain)  $k$ -correction to rest-frame  $B$ . 3C210 is at slightly lower redshift, and was observed with F814W (rest frame  $3700\text{\AA}$ ), resulting in a much smaller  $k$ -correction. Overall, the implied luminosity evolution out to  $z \approx 1$  is quite small compared to the stellar population models (see also van Dokkum & Franx 1996), and more consistent with the open universe models than the closed ones.

## 4 Discussion

Most of the effort directed toward studying distant elliptical galaxies has been aimed either at verifying the gospel of monolithic formation and passive evolution, or at falsifying this scenario as a heinous fiction which flies in the face of the cold logic of hierarchical merging. While most of the evidence presented above would seem consistent with the idea that early-type cluster galaxies have primarily undergone quiescent and passive evolution from  $z \approx 1$  to the present, it is

important to remember the distinction between the galaxies which we *observe* as ellipticals at high redshift and the exact progenitors of today’s elliptical galaxies. While avoiding color-dependent selection effects, morphological selection of high redshift, early-type galaxies may itself introduce biases. By studying things that *look* like ellipticals, one is not necessarily tracing the past history of the actual ancestors to *all* of today’s elliptical galaxies. In particular, if substantial merging has taken place to form the elliptical population, then the objects which are recognizably elliptical galaxies at any redshift may be only the oldest descendents (at that epoch) of that merging process, while more recent (or still-to-be) mergers may not enter into a morphologically-selected catalog. We may only be studying the most dynamically evolved galaxies in each cluster at each redshift, and thus those for which “recent” merger-induced star formation is pushed back to earlier and earlier cosmic times. Moreover, we have not attempted to separate ellipticals from S0 galaxies in our data. Recently, Dressler & Smail (1997) have suggested that there is a marked absence of S0 galaxies in distant clusters imaged by WFPC2. The implication is that the Butcher-Oemler effect may be, in part, a consequence of disk galaxies being transformed into S0s. Depending on the extent of star formation associated with this transformational process, this could provide a mechanism for “re-inflating” the scatter in the combined E/S0 color-magnitude relation at late times, thus giving the impression of no evolution in that scatter.

Regardless, it seems to be clear that a substantial population of early-type galaxies was present in rich clusters out to  $z \approx 1$  and beyond, and that the bulk of their stars must have formed at substantially larger redshifts. Whether *all* ellipticals formed at such early times is less certain, but there is little evidence from the cluster data to indicate that it is not so. It is important to emphasize that the data considered here has primarily been for elliptical galaxies in rich clusters, and that field galaxies might have had rather different evolutionary histories. Kauffmann *et al.* (1996) have used data from the Canada-France Redshift Survey to argue for strong number-density evolution in the population of early-type field galaxies since  $z \approx 1$ . Their argument is basically that the apparent *lack* of strong evolution in the luminosity function of early-type (or at least red) galaxies in the CFRS (Lilly *et al.* 1995) contradicts expectations for passive stellar evolution (see figure 6), and thus must be counterbalanced by extensive number-density evolution. For cluster ellipticals, the hierarchical merging models (e.g. reviewed by White in this volume; cf. also Baugh *et al.* 1996) again predict that while many or most of their *stars* formed at  $z > 1$ , the galaxies themselves assembled late, with  $\sim 70\%$  forming after  $z = 1$ . This is difficult to test from the existing cluster data – the ellipticals already present in clusters at  $z \approx 1$  cannot easily tell us how many more will join them by  $z = 0$ . Moreover, the richest clusters, which are generally those which we observe at high redshift, are quite probably the most unusual and overdense environments at those epochs, and thus are the places where the galaxy merging history is “pushed back” to the earliest cosmic times. The future of this work lies in the investigation of clusters at still larger redshifts, but equally importantly in the

analysis of early-type galaxies across a broad range of environments at  $z < 1$ , from rich clusters through poorer systems and groups and into the field.

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